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3-D MODELING OF SUBIONOSPHERIC VLF PROPAGATION IN THE PRESENCE
OF LOCALIZED D-REGION PERTURBATIONS ASSOCIATED WITH LIGHTNING

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ABSTRACT



A theoretical model of multiple-mode, subionospheric VLF wave propagation in the presence of localized perturbations of the nighttime D-region has been developed. Such perturbations could be produced, for example, by lightning-induced electron precipitation associated with a characteristic type of phase or amplitude perturbation in VLF signals known as "Trimpi" events. Our model assumes that the ionospheric perturbation is slowly varying in the horizontal plane and that mode-coupling within the region of the perturbation is therefore negligible. However, the model does assume mode-coupling along the paths between the transmitter and receiver, the transmitter and the perturbation, and the perturbation and receiver. The model accounts for (1) effects of perturbations with finite extent in the dimension transverse to the great circle (GC) path between transmitter and receiver, and (2) effects of perturbations which lie off the GC path as well as on it. The formulation used for the numerical calculations depends significantly on the mode refractive index of the ambient earth-ionosphere waveguide and the mode refractive index in the region of the perturbation. In the calculations, values for the mode refractive index are determined from the electron-density-versus-altitude profiles of both the ambient and perturbed ionospheres. The results of varying the location of a perturbation along the GC path as well as off the path in the transverse dimension, varying the horizontal scale of the perturbation, and varying the vertical density profile of the perturbation are examined. Values for changes in the amplitude and phase of a received signal were obtained from the model and compared with amplitude and phase measurements of signals received at several receiver sites, operated by the VLF group of Stanford University's STAR Laboratory, from various VLF transmitters during precipitation events. Using realistic values for the ground and ionospheric profile parameters, values of the shift in the amplitude and phase of the signal similar to those measured on signals from several VLF transmitters were obtained using this model. For example, a cylindrically symmetric perturbation of 5λ in horizontal extent due to a 0.2 second burst of precipitating electrons of $\sim 2 \times 10^{-3}$ ergs/cm²-s flux density can produce amplitude changes of ~ -0.3 dB and phase changes of $\sim 2^\circ$ in a signal with a long-distance (800 λ), all-sea-based path between transmitter and receiver. Results from the model suggest that the ratio of the shifts in signal phase and amplitude can be used to determine the distance of the perturbation from the GC path. We conclude that the 3-D theory appears capable of explaining VLF signal measurements showing the "Trimpi" signature.

INTRODUCTION

A three-dimensional method of modeling VLF propagation in the Earth-ionosphere waveguide and how it is affected by the appearance of a localized, D-region disturbance has been developed. Such disturbances can be produced, for example, by lightning-induced electron precipitation (LEP) events, which in turn produce perturbations, known as "Trimpi" events, in the phase and/or amplitude of a received VLF signal [Helliwell et al., 1973; Lohrey and Kaiser, 1979].

Figure 1 from Poulsen et al. [1990] shows the configuration of the problem from a side view and a top view representation. In two-dimensional models [Tolstoy, 1983; Ferguson and Snyder, 1987], the situation depicted in Figure 1a is assumed to be unvarying in the horizontal dimension transverse to the direction of propagation. Thus, a disturbance always occurs directly over the great circle (GC) path between the transmitter and the receiver and

extends to infinity on either side. Our 3-D model accounts for the fact that a typical disturbance is of finite extent in the transverse (as well as along the path) directions. It also accounts for effects of disturbances lying partially or completely off the GC path.

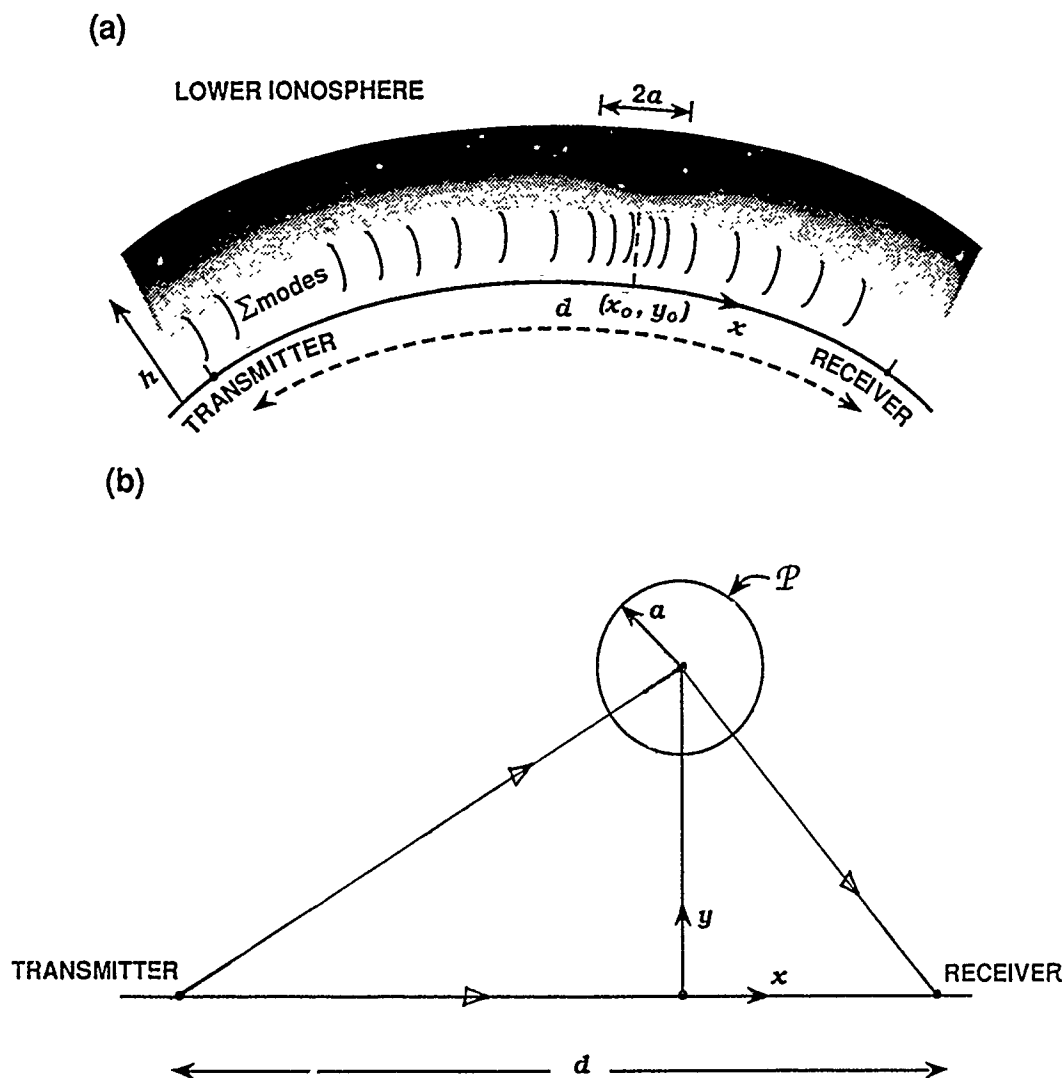


Figure 1. (a) Side view representation of the Earth-ionosphere waveguide between a transmitter and receiver separated by a distance d along the surface of the Earth. The change in electron density with altitude h of the lower ionosphere is represented by the change in shading density. Also represented is a density enhancement region or perturbation of the ambient ionosphere such as those generated by lightning-induced electron precipitation bursts. Such a perturbation, appearing transiently, scatters some of the signal impinging on it and causes a temporary perturbation in the total signal measured at the receiver. (b) A plan view, seen from above, of the situation depicted in Figure 1a showing the three-dimensional configuration of the problem.

For the case of a single dominant waveguide mode, it was found that [Poulsen *et al.*, 1990] the effect of a localized electron density enhancement in the vertical ionospheric density profile is important, i.e., that rather than treating the disturbance as a reflective scatterer, the actual density profile of the disturbance compared to the ambient density profile must be considered in determining the effect that a particular disturbance will have on the propagating VLF wave. Figure 2 shows a vertical density disturbance profile (as well as a typical ambient density profile) that might occur at the center of a disturbance produced by an LEP event at $L \sim 2.5$ [Inan *et al.*, 1988]. The height profile of enhanced ionization within the disturbed region is expected to be important in the multiple-mode case as well, especially since each mode will be scattered a different amount by the same disturbance.

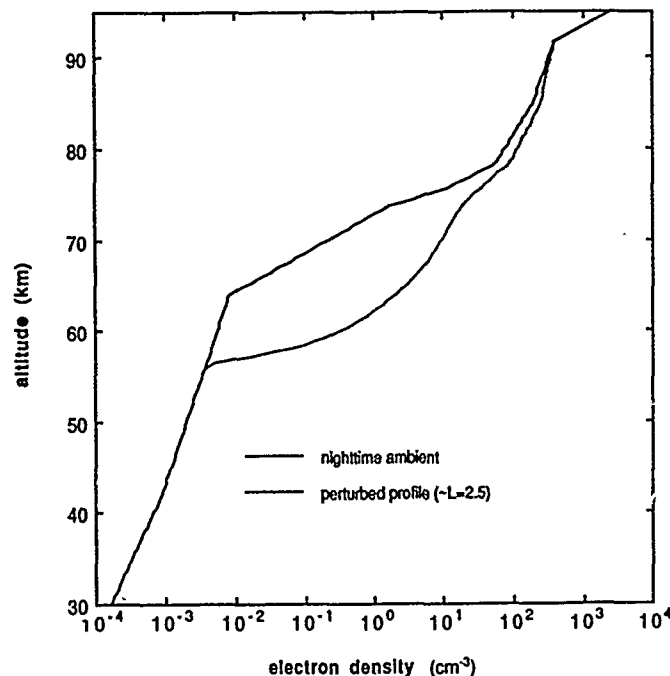


Figure 2. Plot of the electron density distribution versus altitude at the center of a disturbance produced by an LEP event induced by whistlers propagating at $L \sim 2.5$. A typical value of 200 ms for the duration of the lightning discharge and subsequent LEP burst has been assumed in the profile generation. The ambient density profile used in the study is also shown.

THE MODEL

The methodology used in the present 3-D model is depicted in Figure 3. The Long Wave Propagation Capability (LWPC) developed by the Naval Ocean Systems Center [Pappert and Snyder, 1972; Ferguson and Snyder, 1987] is used to calculate the complex signal strength of the wave as it travels along the direct path between the transmitter and receiver ('direct path'), and along the paths from the transmitter to the disturbance ('leg 1') and from the disturbance (or scatterer) to the receiver ('leg 2'). (The LWPC code incorporates a two-dimensional model to calculate signal amplitude and phase along the GC path between the transmitter and receiver and takes into account multiple-mode propagation, changes in ground conductivity along the path, and user-defined density-versus-altitude ionospheric profiles.) Meanwhile, the single-mode 3-D method described in Poulsen *et al.* [1990] is used to calculate the amount of signal scattered by the disturbance towards the receiver on a mode-by-mode basis, assuming that no conversion among modes occurs within the disturbed region. (This implies that a WKB approximation holds;

in other words, that the density profile is slowly varying over distances of $\sim 1\lambda$ in the horizontal directions.) The methodology can be summarized as follows:

- 1) LWPC is used along the GC path from the transmitter to the receiver to find the total electric field arriving along the 'direct path' (E_{direct}).
- 2) LWPC is used along 'leg 1' from the transmitter to the disturbance to find the value of the electric field for each mode n arriving at the disturbance region (e_n).
- 3) The signal strength scattered towards the receiver is calculated for each mode n , one mode at a time, based on the strengths of each of the e_n arriving at the region.
- 4) LWPC is then used along 'leg 2' from the disturbed region to the receiver, using the signal strength values calculated in the previous step as starting values for LWPC (rather than the usual antenna excitation values), to find the total electric field scattered by the disturbance which arrives at the receiver ($E_{scattered}$).
- 5) The direct and scattered electric fields are summed to obtain the total perturbed value of the electric field ($E_{total} = E_{direct} + E_{scattered}$).

The total perturbed value of the electric field at the receiver E_{total} is compared to the total ambient electric field at the receiver E_{direct} to calculate the change in amplitude and change in phase produced by the disturbance. These steps are repeated as the center location, the horizontal extent, and the vertical density profile of the disturbed region are varied. These values can then be compared with values of amplitude and phase perturbations measured on actual transmitter-receiver paths.

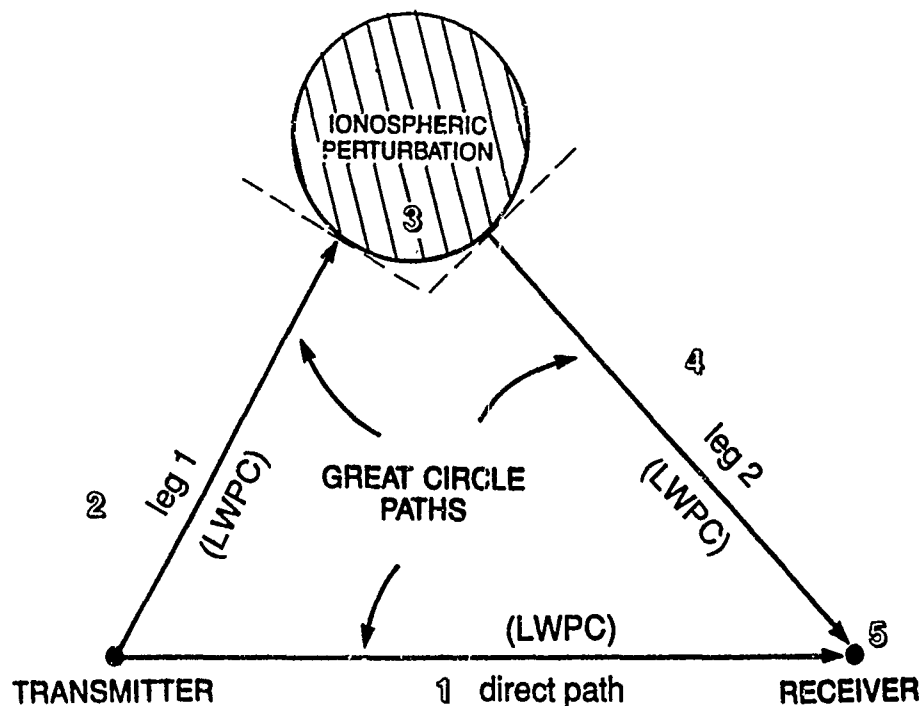


Figure 3. A depiction of the methodology used to calculate the total perturbed value of the electric field observed at the receiver. The numbers correspond to the numbered items given in the text. The Long Wave Propagation Capability (LWPC) is used along the three great circle paths shown, and the single-mode 3-D methodology explained in Poulsen *et al.* [1990] is used on a mode-by-mode basis within the ionospheric perturbation region. See text.

RESULTS

An example of the application of the new 3-D model is presented in Figures 4 and 5 for the propagation path between the NSS transmitter (Annapolis, Maryland) and Stanford University for one particular example of a disturbance. The center of the disturbed region for this case was assumed to have a vertical profile as shown in Figure 2. This was scaled back to the ambient profile values in the transverse directions proportional to a gaussian function to produce a cylindrically symmetric transverse profile with ~ 50 km radius. Figure 4 shows the amplitude and phase plots along the three 'legs' as discussed above. Notice that along the scattered path ('leg 2'), a larger number of modes of comparable amplitude (produced at the scatterer) result in a more complicated amplitude variation than along 'leg 1'. Also note that the amplitude scale for 'leg 2' is much smaller than for the other two legs since the scattered components for each mode are smaller than the incident ones for the disturbance profile used here (Figure 2).

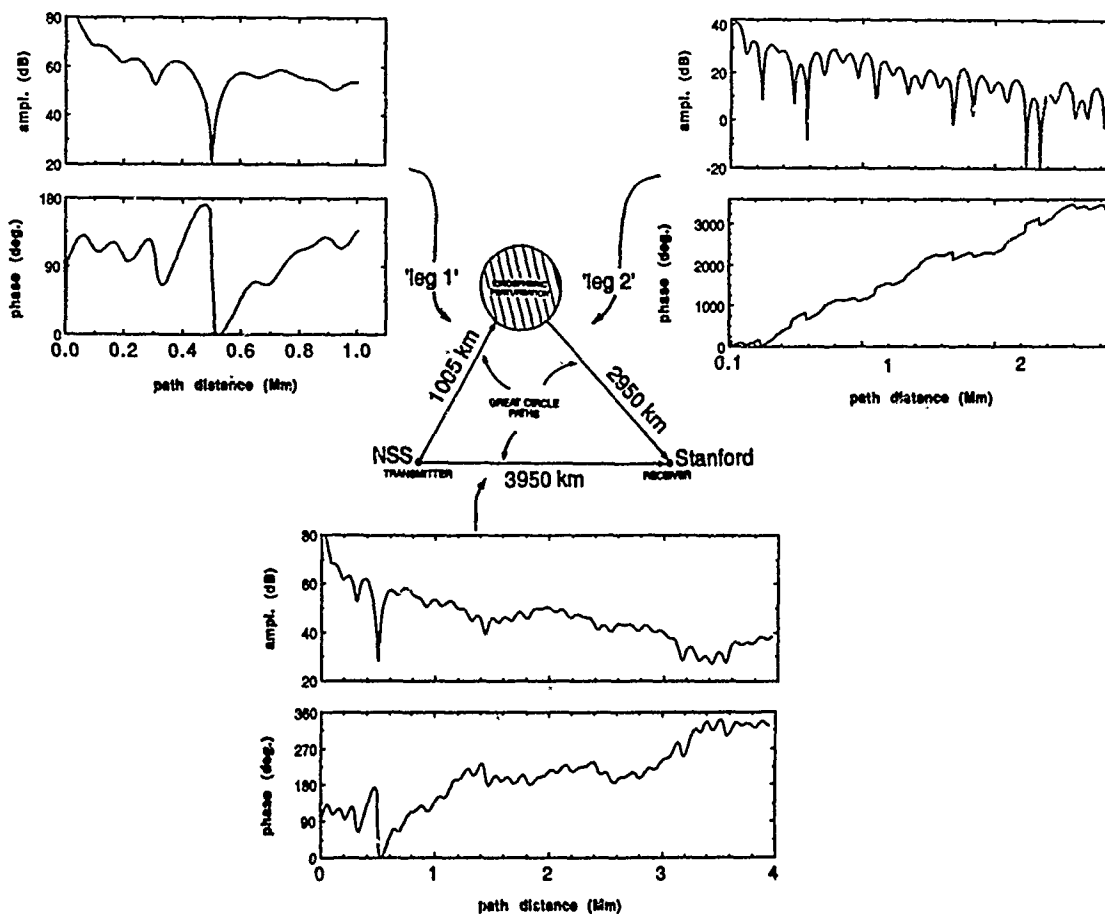


Figure 4. Amplitude and phase plots of a signal propagating along the three great circle paths shown for one particular example of a disturbed situation. The radius of the disturbance in this case is 50 km and the center of the disturbance is located 1000 km along the great circle path from NSS to Stanford and 100 km away from this 'direct path' on its north side. The lengths of the three paths are given in the center part of the figure (Note: not drawn to scale).

Figure 5 shows the relative signal strength and phase of each propagating mode at various points along the three paths of propagation for the specific example indicated (NSS to Stanford; disturbance of 50 km radius centered 100 km north of a point 1000 km along the GC path from NSS). The value in brackets beside each phasor diagram indicates the full-scale value of the relative signal strength (for that diagram). As was noted in the previous paragraph, the phasor diagrams show larger amplitudes of higher-order modes being scattered by the disturbance that subsequently propagate along 'leg-2'. Even at the receiver, there are substantial amounts of these higher-order modes still present. For this example the change in total received amplitude of the signal is ~ 0.12 dB, accompanied by a phase change of ~ 0.1 degrees. These values are within the range of measured amplitude and phase changes that occur on the NSS-Stanford path in LEP events [Wolf, 1990] (A bar graph showing the percentage of amplitude Trimpi events falling within spaced decibel ranges measured at Stanford on the NSS signal is given in Figure 5).

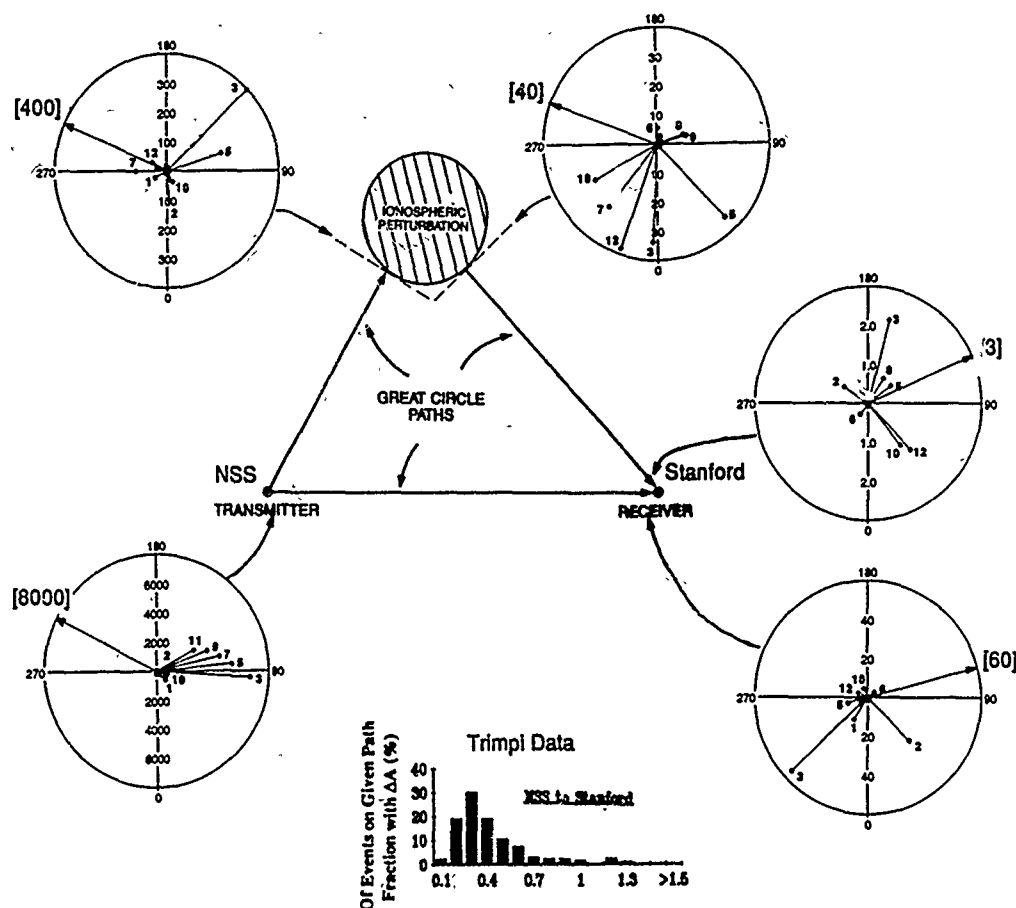


Figure 5. Phasor diagrams of the relative signal strength and phase of each mode of the propagating signal located at the points indicated by an arrow along the three propagation paths for the example described in Figure D. The value in brackets by each diagram indicates the full scale value of the relative signal strength for that diagram. Also plotted is a distribution bar graph showing the percentage of amplitude Trimpi events falling within spaced decibel ranges typically measured at Stanford on the NSS signal.

While the results in Figures 4 and 5 are for one particular size and location of the disturbance, the amplitude and phase changes at the receiver are expected to depend strongly on the location of the receiver as well as the disturbed region. This is illustrated in Figure 6, which shows an amplitude and phase plot of a two-dimensional (LWPC-only) calculation of the signal strength along the NSS to Stanford path for an ambient case and a case with a disturbance 100 km wide located at a point 3 Mm from NSS (and assumed to lie directly over the GC path and extend to infinity in the transverse directions). The amplitude and phase changes produced by the disturbance in this example change very little at some of the points along the path beyond the disturbance, while at other locations, changes larger than 10 dB may be observed. Similarly, for a fixed receiver point, some locations of the disturbance are expected to produce larger signal changes than other locations.

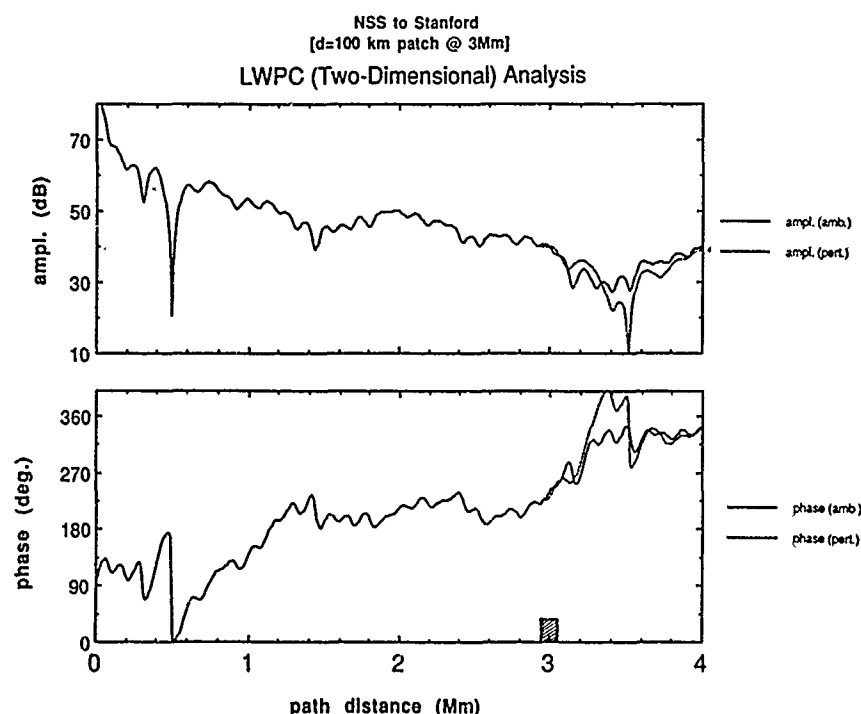


Figure 6. Amplitude and phase plots of a two-dimensional (LWPC-only) calculation of the signal strength along the NSS to Stanford path for an ambient case and a case with a disturbance 100 km wide centered at a point 3 Mm from NSS, having the disturbed electron density profile shown in Figure 2.

CONCLUSIONS

In summary, a new methodology to account for the effect of localized, off-great-circle path disturbances on propagating VLF waves has been developed. It utilizes the LWPC software developed by the Naval Ocean Systems Center and the results of *Poulsen et al.* [1990]. Preliminary results of the model are in agreement with observations of LEP event effects along typical paths. The model is applicable to a wide range of disturbance types in the lower ionosphere that can be modeled by a vertical density profile and that satisfy the WKB approximation. And this model can be generalized to account for mode coupling within the disturbed region itself (non-WKB cases).

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